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A BRIEF SURVEY OF DIRECT ENERGY CONVERSION DEVICES FOR POSSIBLE SPACE VEHICLE APPLICATION

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SUMMARY

A brief review is given of various types of devices for converting heat or radiant energy directly into readily available electrical form. These devices include the thermoelectric generator, the photovoltaic cell, the thermionic converter, and the photoemissive converter. The discussion is from the point of view of possible space-vehicle application. An attempt is made to indicate in a general way the present state of development, the advantages and difficulties associated with each device, and to suggest general lines of future research.

INTRODUCTION

Tremendous amounts of energy expended in a relatively short period of time are required to place a space vehicle in orbit. After the vehicle is in orbit, or at least has been given sufficient energy relative to the earth that its path of motion nowhere traverses the denser regions of the atmosphere, a relatively low power source of long duration is necessary if maximum utility of the vehicle is to be realized. For example, one of the more obvious possible uses of an earth satellite is to transmit or relay television and radio signals. Such an application is only fully effective as long as the power source lasts. In order to obtain the most benefit from the huge economic effort required to launch a space vehicle, the life expectancy of the power source should approximate that of the vehicle.

The various energy sources may be classified into three groups; chemical, solar, and nuclear. In most cases, the energy from these sources is available in the form of electromagnetic radiation or heat energy. The form in which the energy is finally desired is usually electrical energy because this form is generally more convenient than any other. The problem then is that of converting heat or radiation into usable electrical energy. The usual process employs a thermodynamic working fluid with a mechanical device to convert a portion of the heat into mechanical energy, and then another mechanical device to convert the mechanical to electrical energy. This process is presently the best understood.

There are, however, devices that transform heat and radiant energy to electrical energy without going through the intermediate mechanical phase, at least on a macroscopic scale. Such devices are known as direct conversion devices. Because of the fact that no moving parts are involved, such devices are essentially simple mechanically and may have an almost indefinite life. Of the various devices, there seem to be four types at the present time that have been developed sufficiently to be considered as possible practical means for effecting the desired conversion. These are the thermoelectric generator, the photovoltaic cell, the thermionic generator, and the photoemissive generator.

Thermoelectric Generators

The physical phenomena that form the basis of operation of the thermoelectric generator have probably been known for the longest time. These phenomena are the Seebeck effect, the Peltier effect, and the Thompson effect. The Seebeck effect, discovered in 1822, consists essentially of the fact that if a closed circuit be made of two conductors of dissimilar material and one junction is maintained at a different temperature than the other, an electric current will flow in the circuit. The related Peltier effect, discovered in 1834, is that heat is produced or absorbed reversibly at the junction of two dissimilar metals depending on the direction of current through the junction. The Thompson effect is that a temperature difference between two points in a homogeneous substance produces a potential difference between the points. All these effects are basic to the operation of the familiar thermocouple.

One might well ask "Why the sudden interest in thermopiles?" The answer to this question lies in the deeper understanding of the phenomena obtained from relatively recent advances in solid state physics, and the resulting improvements in output and efficiency associated with the use of new materials. A detailed exposition of thermoelectric effects and their engineering applications is given by Ioffe in reference 1.

A schematic diagram of a thermoelectric converter is shown in figure 1. The use of several different substances connected in series both thermally and electrically is typical of present practice.

Although different for different materials, the thermoelectric voltage per degree of temperature difference between the hot and cold junctions of a particular material varies approximately linearly with temperature. Thus, at some particular temperature, this voltage may be maximized by a proper choice of materials. Factors other than the thermoelectric voltage, however, are also of importance. When one junction is maintained at a different temperature than the other, heat is conducted from the hot junction to the cold junction. This conduction represents an energy loss. Another important source of loss is the Joule heat developed within the material. Detailed analysis of the problem shows that the various effects can be combined into a single parameter that is indicative of the effectiveness of the material in a thermoelectric device. This parameter is

$$Z = \frac{a^2}{\kappa \rho}$$

where a thermoelectric voltage per degree

κ thermal conductivity

ρ electrical resistivity.

Typical variations of the parameter Z with temperature are indicated in figure 2. By choosing proper materials and by adjusting the geometry of the various blocks making up the generator so that each junction is operating near its most effective condition, the efficiency of the thermoelectric generator can be made many times that of the usual thermocouple.

A figure of merit that is frequently used in comparing thermoelectric generators is the ratio of the generator output to that of an idealized machine operating with Carnot cycle efficiency between the same temperatures. Efficiencies of the order of six percent of the Carnot efficiency have been achieved, and the hope expressed that future research may raise this number to 10 or 12 percent of the Carnot efficiency. At present, the weight of a thermoelectric generator is approximately 1 lb. per watt or 1,000 lb. per kilowatt. The objectives of research at the present time are to improve this figure by finding suitable thermoelectric material combinations that can work effectively at higher temperatures, thereby improving the ideal efficiency and to find new materials or new methods of using present materials to yield effectively a higher value of the characteristic quantity Z.

Photovoltaic Cells

Photovoltaic cells are of relatively recent origin. They

have been used commercially to supply power for some rural telephone lines by converting solar radiation directly into electrical energy. They are also supplying the long-term low-level power on the Vanguard satellite. The general principles of operation of such a cell are illustrated in figure 3. See also Reference 2. Pure crystaline silicon is normally an n type semiconductor. If enough of an element from group III in the periodic table, for example, boron, is incorporated in the silicon crystal structure, the substance is transformed to a p type semiconductor. When the two layers are in contact with no current flowing, the equilibrium condition is for the potential corresponding to the Fermi level in each layer to be the same. The Fermi level is the level that has a probability of one-half of being occupied by an electron. In p type conductors the Fermi level is close to the top of the valence band, whereas in n type conductors it is close to the bottom of the conduction band. The boundaries of these bands are, of course, only sharp at a temperature of absolute zero.

The typical silicon cell consists of a silicon crystal with from one to two square centimeters of surface area into one face of which boron has been diffused to form a p layer about one micron thick. The total thickness of the crystal is about one-half millimeter. Photons in the visible range penetrate the crystal to a depth of the order of a micron. When a photon is absorbed, a hole is formed in the valence band and an electron is added to the conduction band. The result

is the same regardless of whether the photon is absorbed in the boron-silicon layer or in the pure silicon. In either case, the electron is available to travel through an external circuit connecting the n layer to the p layer. However, excess electrons in the p layer near the p-n junction are attracted to the lower energy level of the n layer conduction band, thus creating a potential difference between the layers. This potential difference is used to force the electrons through an external circuit. As the temperature is increased, the limits of the various bands become less distinct. This spreading of the band limits results in an increase in the number of electrons in the conduction band, and simultaneously a decrease in the open circuit potential. Thus, the internal resistance of the cell decreases but the generated voltage also decreases with increasing temperature. As compared with an ambient temperature of about 100° F, silicon photovoltaic cells suffer a severe decrease in maximum power output if the cell temperature increases. In fact the maximum power output decreases by about 50 percent as the cell temperature increases from 100 to 300° F. Performance characteristics of a sample silicon photovoltaic cell are shown in figure 4. These characteristics were obtained with the illumination held constant at a value of about one-fourth that of the sun at ground level.

The conversion efficiency of photovoltaic cells can be fairly high, up to about 10 to 12 percent, if the load impedance

is carefully matched to that of the cell at its operating conditions of irradiance and temperature. Under ideal conditions, the weight of the silicon in the cells would be about 20 lb. per kw. if a cell efficiency of 10 percent is assumed and the irradiance is 1.4 kw./sq. meter, approximately the irradiance outside the earth's atmosphere. Unfortunately, the silicon crystal that makes up each cell is extremely fragile. Furthermore, at the present time, the output of each cell is only of the order of 0.01 watt at approximately 0.5 volt. These facts together with the necessity for keeping cell temperature low for higher efficiency, mean that a substantial supporting structure is required in order to obtain a device sufficiently rugged to withstand ground handling and launch, and that the necessary wiring can be extensive and relatively heavy. Estimates have been made of the weight of a silicon cell array sufficiently extensive to have an output of a few kilowatts when exposed to solar radiation outside the earth's atmosphere. If present commercially available cells are used, the unit weight would be about 350 lb./kw. Developmental-type research might reduce this weight to about 200 lb./kw. The use of newly-developed more effective materials and the possibility of increasing the size of the individual crystals would, of course, make possible further substantial reductions in unit weight.

A little thought will show that if the leads form a substantial part of the total weight, the weight per unit power

will increase with increasing power. Since the inverse is also true, photovoltaic cells are comparatively better in small sizes. It is in this range of small powers that, in fact, photovoltaic cells have been used in the past.

Thermionic Converters

Thermionic converters are essentially diodes. The possibility of using a diode as a heat engine was first investigated in detail by G. N. Hatsopoulos in his doctoral dissertation (ref. 3). Further development of this subject is given in references 4, 5, 6, 7, and 8.

A simplified sketch of a vacuum thermionic cell and the corresponding energy-level diagram is given in figure 5. When the cathode is heated, some of the electrons absorb enough energy to overcome not only the internal cathode work function (ϕ_c) but also the potential field of the previously emitted electrons (space charge). These electrons of relatively high energy then continue to the anode where they lose their kinetic energy plus potential energy of amount ϕ_A electron volts per electron. If the resulting energy level EF_A of the electrons in the anode is more negative than the original level EF_c in the cathode, the difference in energy level, V_o, can be used to drive the electrons through a machine and thus do useful work. Since the diode current is limited by the space charge potential field, one of the most serious problems connected with this device is the problem of reducing the peak space

charge potential to an optimum level while maintaining a high conversion efficiency. A part of this problem is that of reducing the difference between the energy level at the anode surface and the peak energy level in the space charge region. Several means have been proposed and some have been tested experimentally. An examination of the laws for the distribution of space charge about an electron emitter, which were formulated by Langmuir (ref. 9), indicates that one way of reducing both the peak space-charge potential and the difference in energy level between the peak space-charge level and the level at the surface of the anode is to put the anode very close to the cathode. This method, in fact, has been investigated by Hatsopoulos and Kaye (ref. 5) and by Webster and Beggs (ref. 8) for spacings as close as 0.0005 in. The degree of success attained is illustrated by the results presented in figure 6, taken from reference 5. The power output is plotted against the output voltage in figure 6a, and the thermal efficiency of the device is plotted against the output voltage in figure 6b. The relatively high power density is to be noted. This characteristic means that the specific weight of such a converter should be relatively low. This is particularly true in view of the fact that no structure is needed to maintain a vacuum in outer space since the ambient pressure at an altitude of a few hundred miles is much less than the lowest vacuum attainable on the ground with presently available equipment.

Another method of overcoming the space-charge problem of the thermionic converter is by the introduction of cesium vapor. The process, illustrated diagrammatically in figure 7, operates in approximately the following manner. Cesium vapor is introduced into the evacuated chamber of the device. The vapor tries to coat all of the interior surfaces. The cathode, however, is too hot to permit condensation. If the cathode electron work function, that is, the work necessary to remove an electron from the surface of the cathode is more than the ionization potential of cesium, then when a neutral cesium atom hits the cathode, the atom will bounce back from the hot surface as a positively charged cesium ion. An accumulation of such ions in the space between the cathode and anode will tend to neutralize the electron space charge. The distribution of potential between the cathode and anode is then changed from that shown by the dotted line in figure 7 to that shown by the solid line. The advantages of this method are that cesium will collect on the surface of the anode to, in general, give it a lower work function and that the spacing between the anode and cathode can be large compared to the vacuum diode.

Experimental data on such a cesium vapor diode have been presented by Volney C. Wilson in reference 6. In general, the maximum current and power densities were about four or five times those of the high vacuum thermionic converter. For space

applications, however, the cesium vapor converter may have certain disadvantages. The converter element, or at least the space between the cathode and anode must be kept gastight. From the point of view of providing a container strong enough to hold the cesium vapor, the problem is not too difficult and would not involve a large weight penalty if it were not for the fact that the wall thickness of the container is dictated not so much by strength considerations as by the condition that it must be able to withstand meteorite impact. As is indicated in reference 10, meteorites can have remarkable penetrating power. The meteorite problem would have to be carefully considered in the design of a cesium vapor thermionic converter for use in a space vehicle.

Two other possible schemes for controlling or neutralizing the space charge have been mentioned in the literature (ref. 3) but as yet have not been thoroughly tested. These are: (a) the use of crossed electromagnetic fields, and (b) the use of a grid as a third element in the device. There is little doubt that converters can be made to operate on either of these principles. The important questions to be answered, and they can only be answered experimentally, are for case (a); Is the power required to maintain the electric and magnetic fields so large as to make this method unattractive?; and for case (b), Does the current drain to the grid represent too large an energy loss to be tolerated?

The temperatures at which the thermionic converter operate are of interest. For the case cited in figures 6a and 6b, the cathode temperature is about 2300° F and the anode temperature 1000° F. The cathode temperature is not so high as to be difficult to obtain or contain, and the anode temperature is sufficiently high that no special difficulty should be encountered in disposing of the waste heat by radiation, the only method available in space. Estimates have been made of the weight of a thermionic converter used in connection with a solar energy collector at from 40 to 80 lb. per kw. including the weight of the collector.

Up to the present time, the thermionic converters have only been built in laboratory-sized units having cathode areas varying from a small fraction of a square centimeter to about one square centimeter. Developmental research is needed to increase the size of the units so that packaged converters delivering power up to several kilowatts are available. Since the efficiency of the converter is greatly affected by the work function of the anode, basic research is needed in an attempt to find substances or combinations of substances having a low work function at the operating conditions of the anode. Much work has, of course, been done on finding suitable substances for cathodes at their normal operating temperatures in connection with vacuum tube filament research. The answers desired in the present case are of a similar nature but for different conditions.

Photoemissive Converter

The last class of converters to be discussed in this paper is the photoemissive converter. This device makes use of the photoelectric effect, that is, the ejection of an electron from a surface upon absorption of a photon of sufficient energy. A schematic sketch and electric potential diagram for a photoemissive converter are given in figure 8. Light passes through a transparent conductive coating and is absorbed by the photosensitive substance which forms the cathode. Electrons are emitted from the cathode and collected by the anode. Except for the agent causing the emission of electrons, the method of operation is almost identical with that of the thermionic converter. By the same token, one of the principal problems associated with the operation of the device, namely, control of the space charge is almost the same as for the thermionic converter. Important practical differences, however, result from the fact that the cathode temperature need not be high. In fact, the cathode temperatures may be sufficiently low that lightweight materials such as plastics can be used for the structural components of the device. Although no experimental data on a practical device have been obtained, the inherent characteristics of the device are such as to make it appear very attractive and worthy of detailed investigation.

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CONCLUDING REMARKS

This brief review has attempted to indicate the types of devices that are presently being considered for use on space vehicles for converting heat or radiant energy to electrical form, and to give some idea of their present state of development. One thought that has not been mentioned is the possibility of combining two or more types of devices into a single unit. This possibility appears to be advantageous in the case of the thermionic converter and the thermoelectric converter. The thermionic converter rejects heat at temperatures of the order of 1000° F. This heat could represent the input to a thermoelectric converter that would later radiate the heat away at a lower temperature, say, 300° F to 500° F, and contribute substantially to the power output of the entire unit.

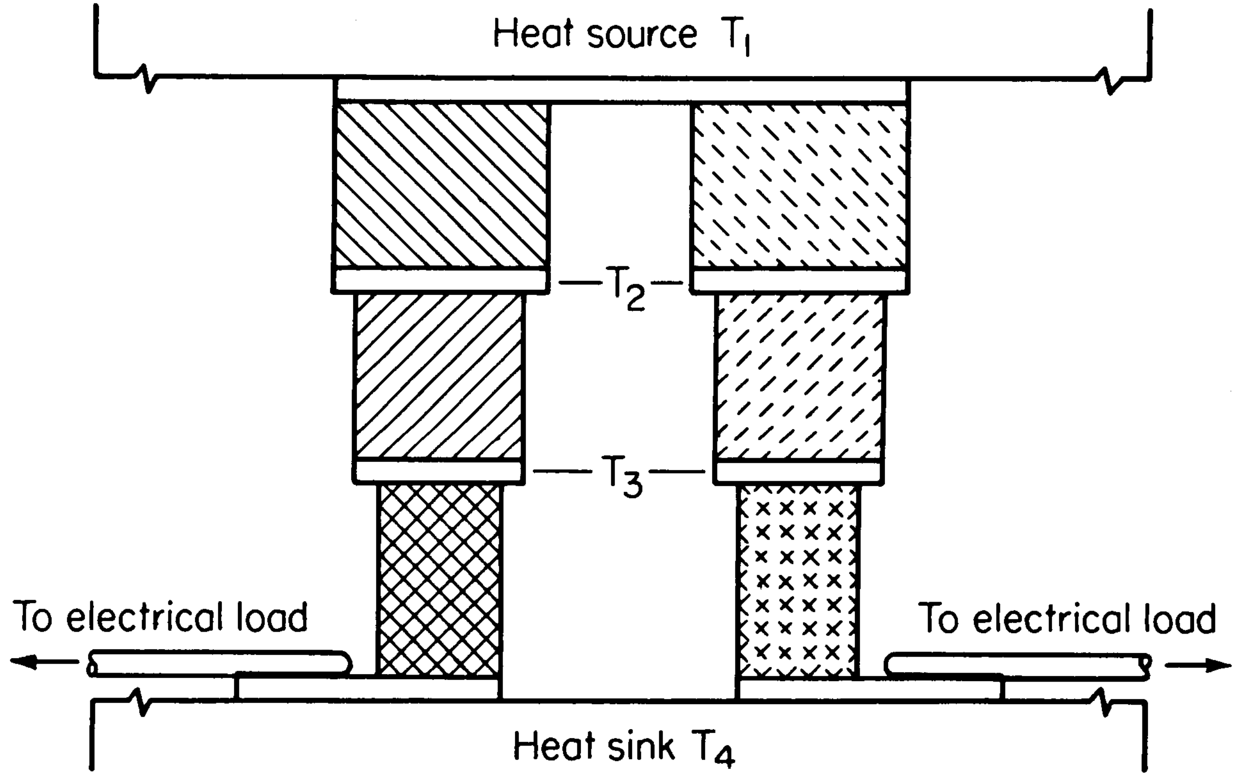


Figure 1.- A possible three stage thermocouple arrangement

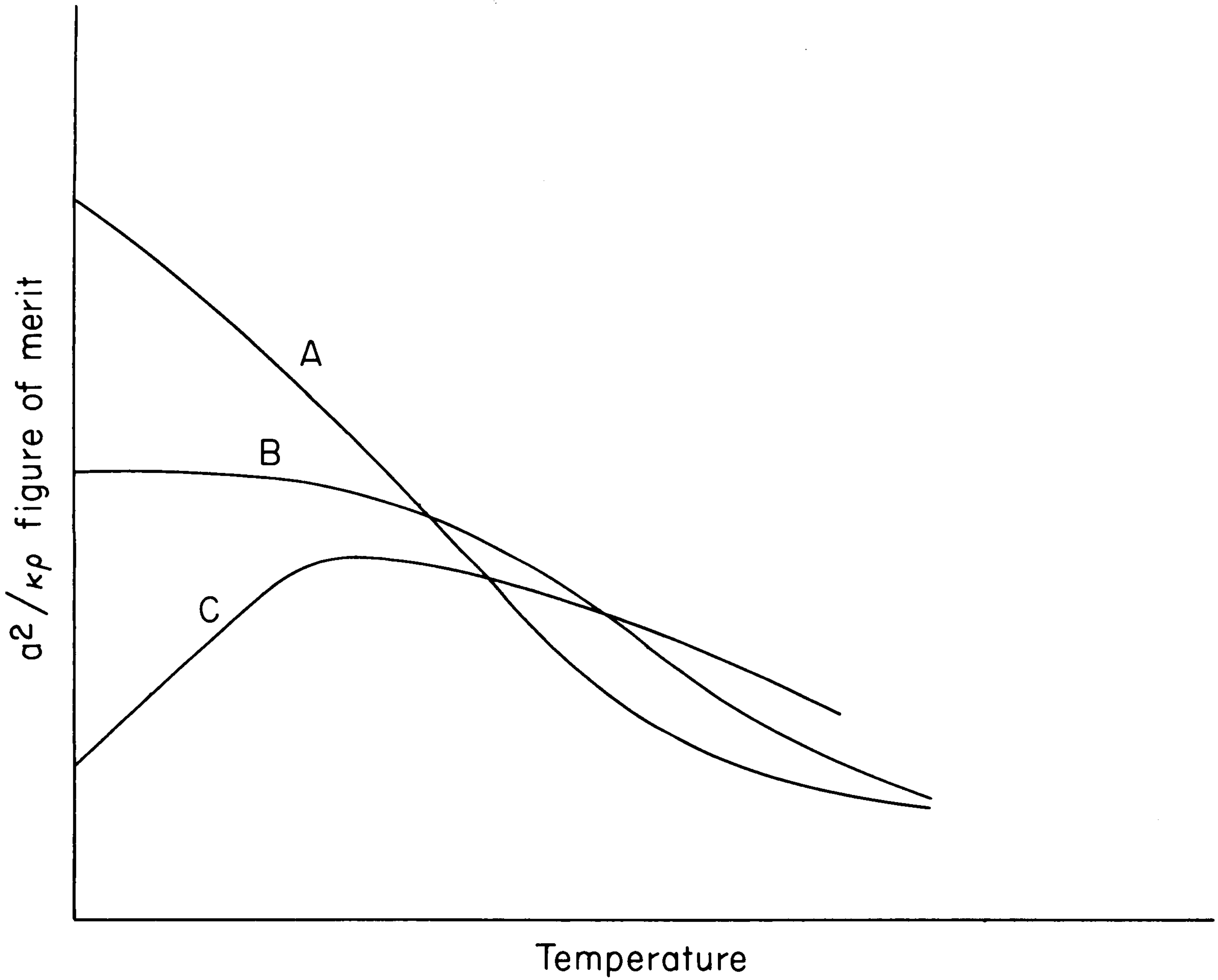
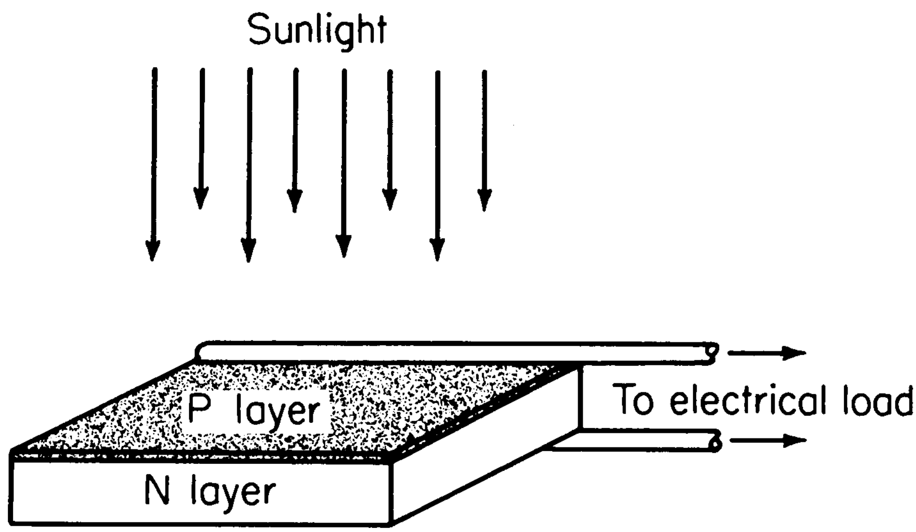
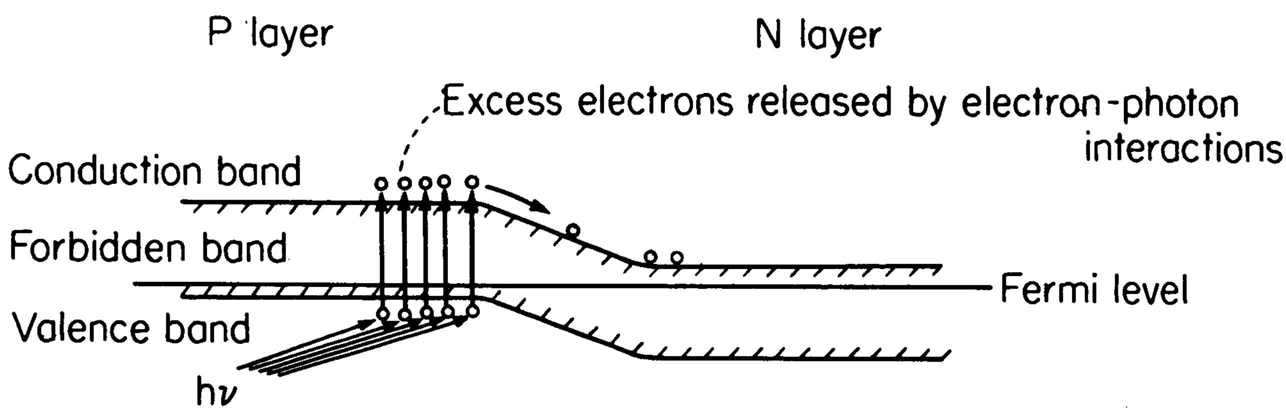


Figure 2. - Typical variation of thermoelectric figure of merit with temperature for various substances



Silicon photovoltaic cell



Silicon photovoltaic cell energy level diagram

Figure 3. – Schematic and energy level diagram for a silicon photovoltaic cell

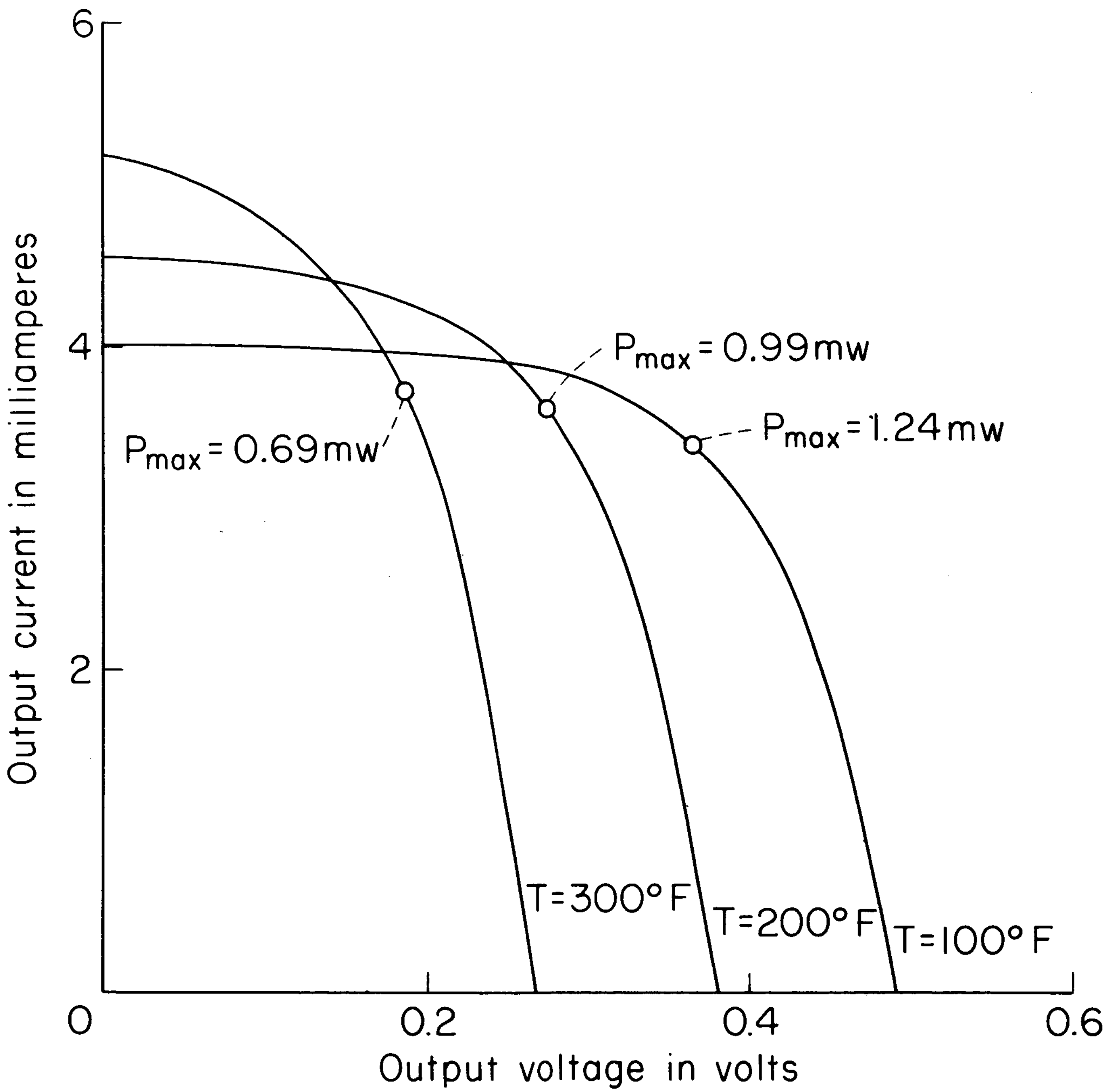


Figure 4a. – Typical output characteristics of a silicon photovoltaic cell with constant irradiance

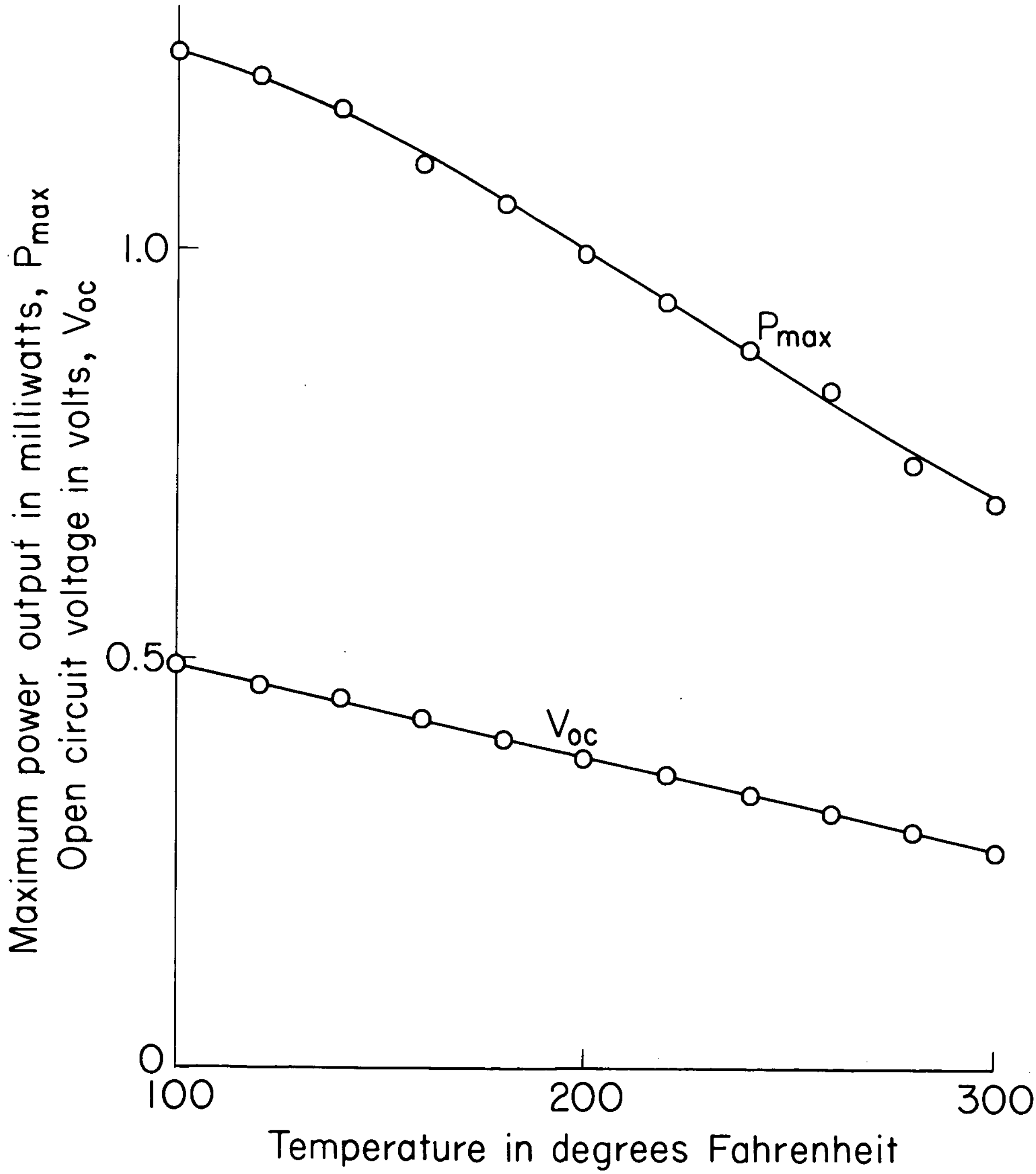


Figure 4b.– Maximum power output and open circuit voltage versus temperature for a typical silicon photovoltaic cell with constant irradiance

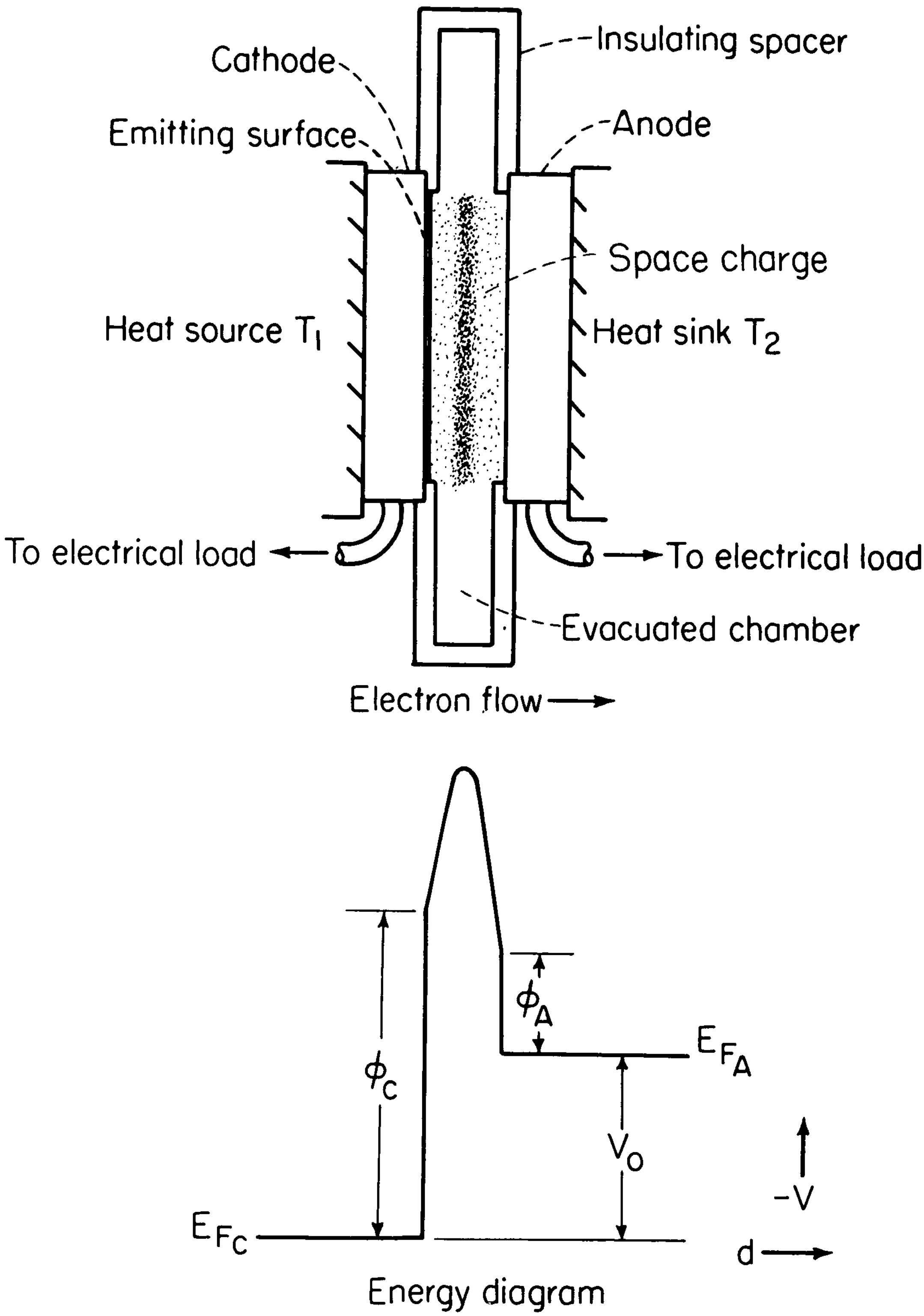


Figure 5. – Vacuum thermionic cell schematic and energy diagram

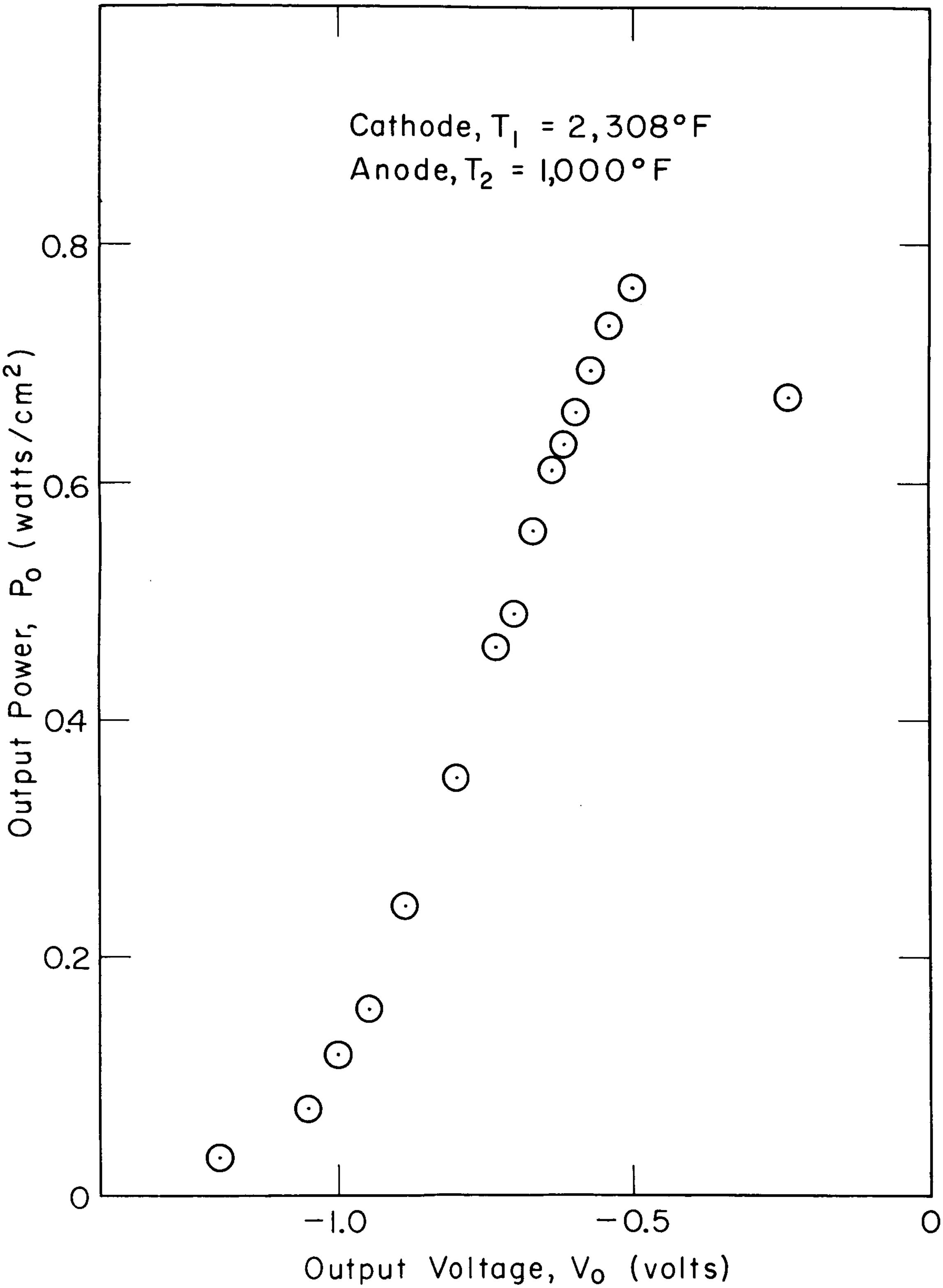


Figure 6a.– Experimental power output versus output voltage for diode configuration

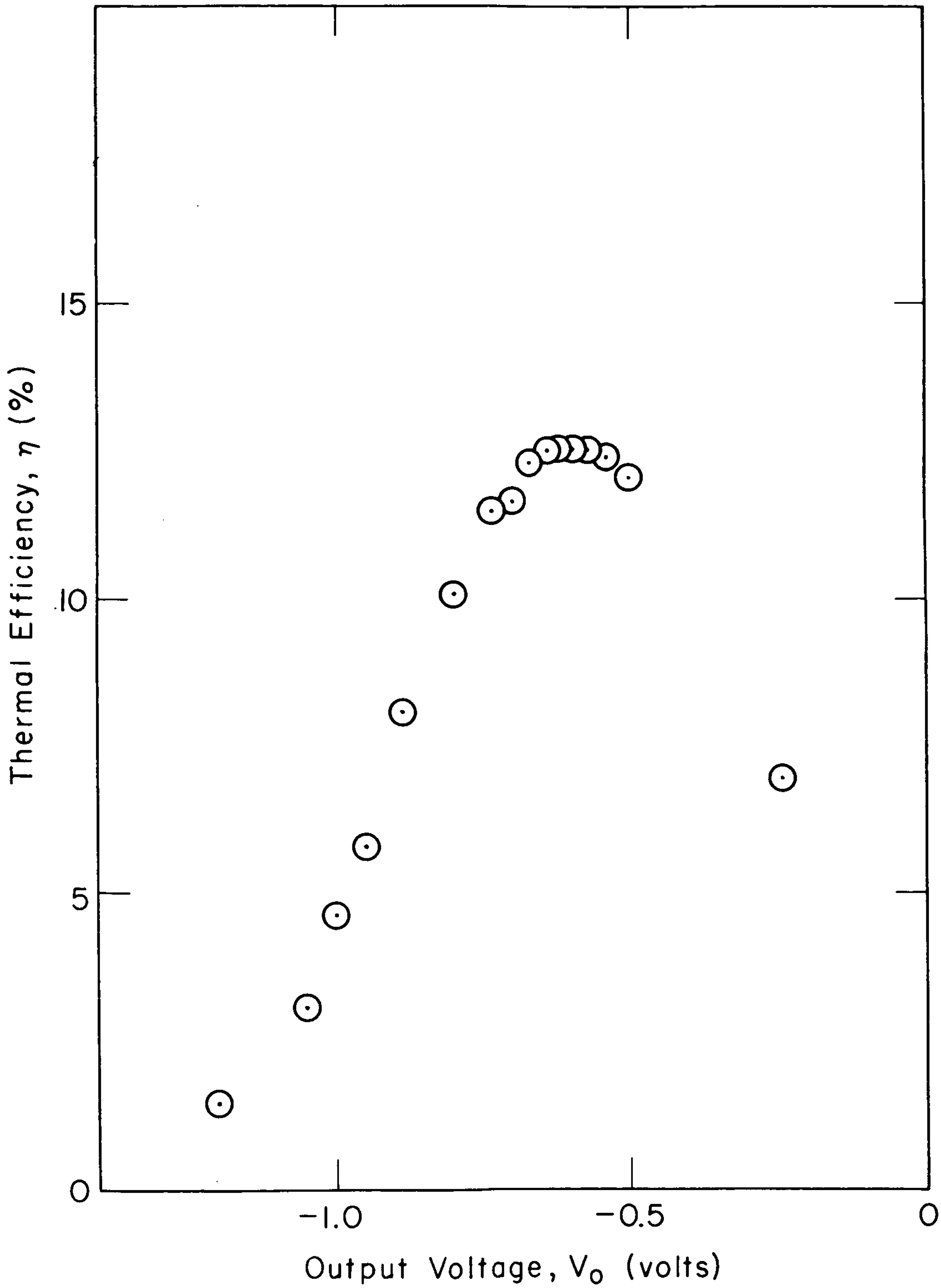


Figure 6b.—Experimental results for sample diode configuration of thermoelectron engine

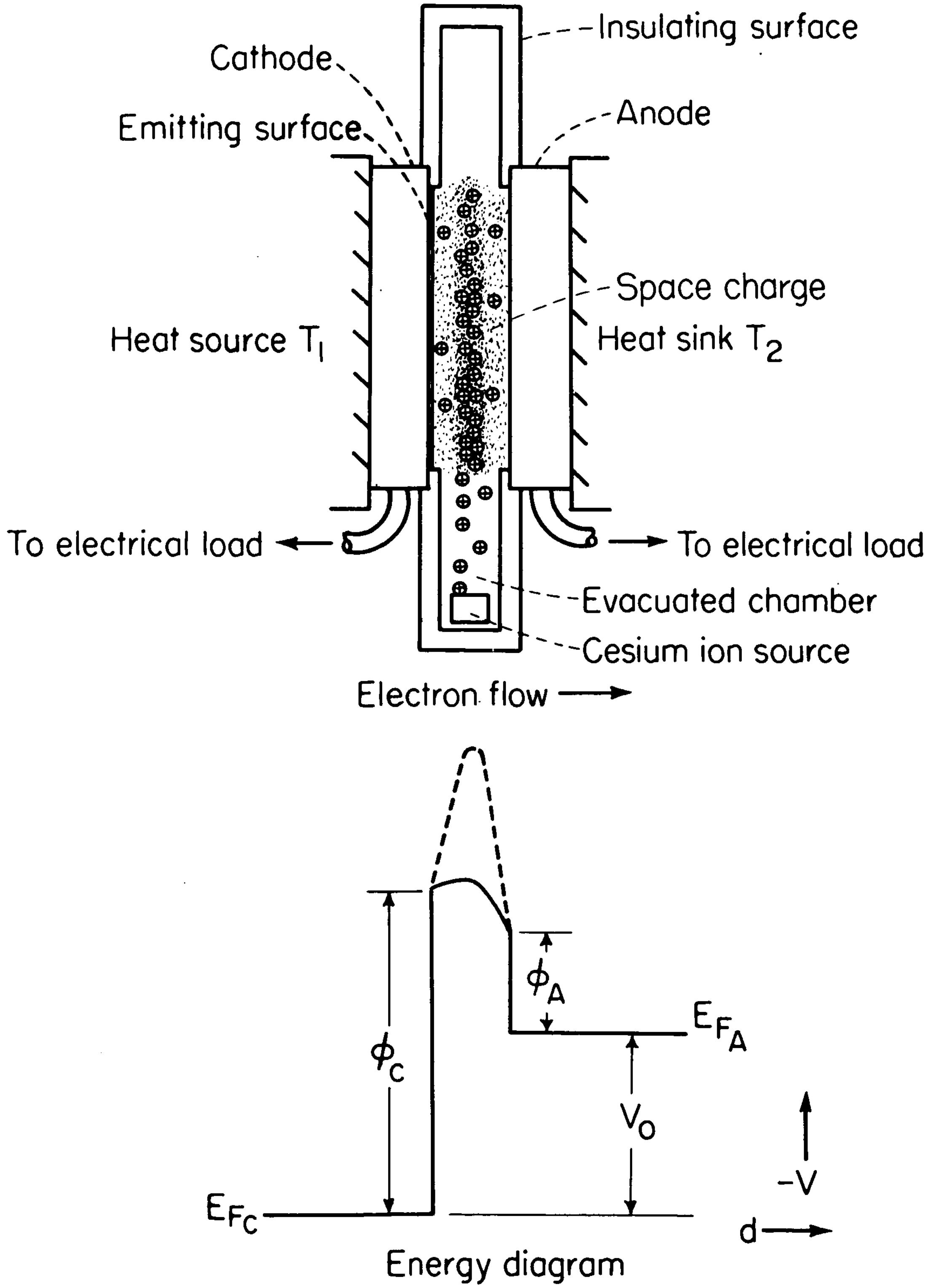


Figure 7.– Thermionic cell space charge neutralization by cesium ions

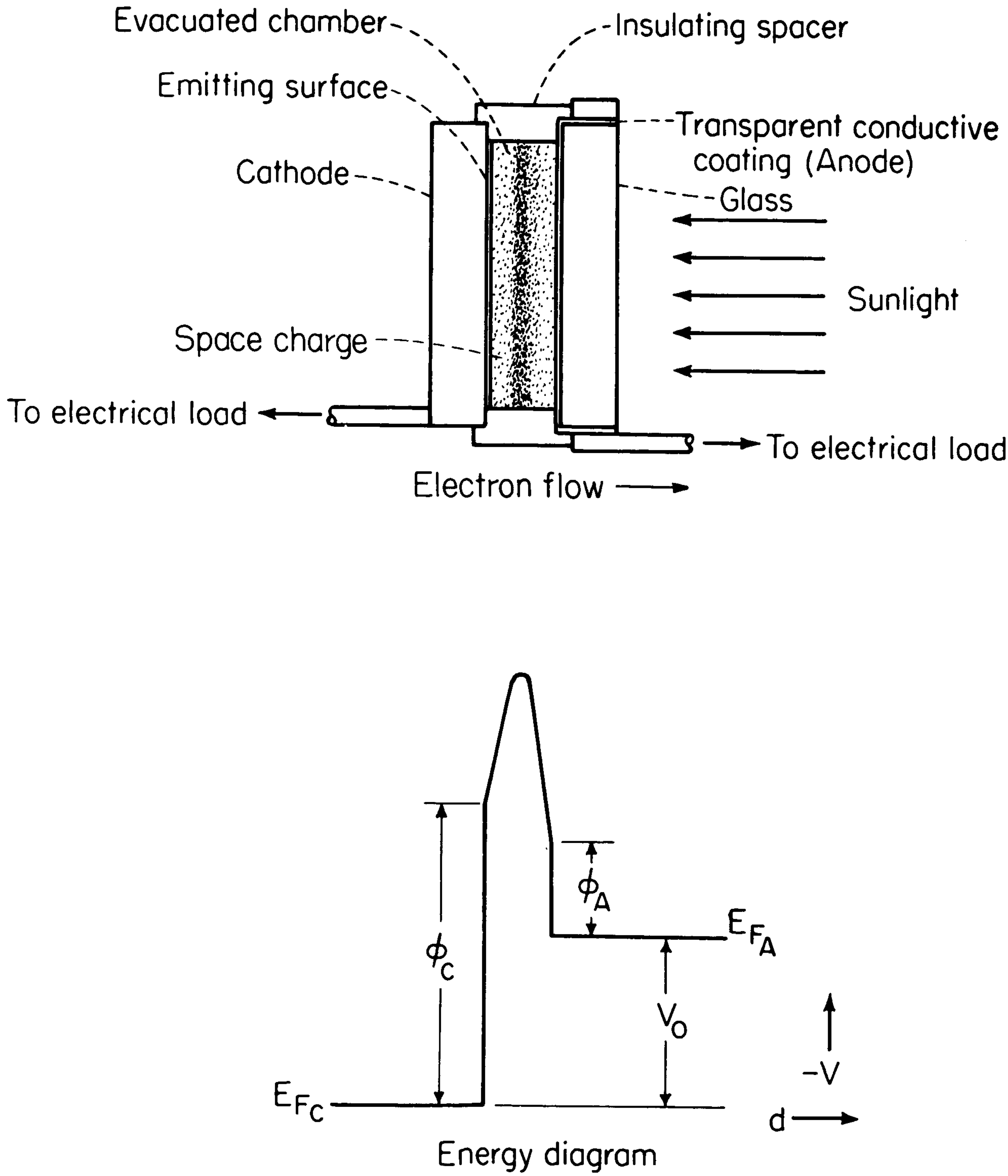


Figure 8.–A possible photoemissive cell